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# The Beat is Getting Stronger: The Effect of Atmospheric Stability on Low Frequency Modulated Sound of Wind Turbines

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## SUMMARY

Sound from wind turbines involves a number of sound production mechanisms related to different interactions between the turbine blades and the air. An important contribution to the low frequency part of the sound spectrum is due to the sudden variation in air flow which the blade encounters when it passes the tower: the angle of attack of the incoming air suddenly deviates from the angle that is optimized for the mean flow. Hitherto, low-frequency sound from wind turbines has not been shown to be a major factor contributing to annoyance. This seems reasonable as the blade passing frequency is of the order of one hertz where the human auditory system is relatively insensitive. This argument, however, obscures a very relevant effect: the blade passing frequency modulates well audible, higher-frequency sounds and thus creates periodic sound: *blade swish*. This effect is stronger at night because in a stable atmosphere there is a greater difference between rotor averaged and near-tower wind speed. Measurements have shown that additional turbines can interact to further amplify this effect. Theoretically the resulting fluctuations in sound level will be clearly perceptible to human hearing. This is confirmed by residents near wind turbines with the same common observation: often late in the afternoon or in the evening the turbine sound acquires a distinct ‘beating’ character, the rhythm of which is in agreement with the blade passing frequency. It is clear from the observations that this is associated to a change toward a higher atmospheric stability. The effect of stronger fluctuations on annoyance has not been investigated as such, although it is highly relevant because a) the effect is stronger for modern (that is: tall) wind turbines, and b) more people in Europe will be living close to these wind turbines as a result of the growth of wind energy projects.

## 1. INTRODUCTION

Modern onshore wind turbines have peak electric power outputs of around 2 Mw and tower heights of 80 to 100 meters. In 2003, 75% of the global wind power peak electric output of 40 Gw was installed in the European Union. The original European target for 2010 was 40 Gw, but the European Wind Energy Association have already set a new target for 2010 of 75 Gw, of which 10 Gw is projected off-shore, while others have forecast a peak output of 120 Gw for that year [1]. Whether this growth will actually occur is uncertain; with the proportional increase of wind energy in total electric power the difficulties and costs of integrating large scale windpower with respect to grid capacity and stability, reserve capacity and CO<sub>2</sub> emission reductions are becoming more prominent (see, e.g., [31, 32]). However, further expansion of wind energy is to be expected, and as a result of this (predominantly on-shore) growth an increasing number of people may face the prospect of living near wind farms, and have reason to inquire and perhaps be worried about their environmen-



tal impact. Visual intrusion, intermittent reflections on the turbine blades, as well as intermittent shadows (caused when the rotating blades pass between the viewer and the sun), and sound, are usually considered potentially negative impacts.

Atmospheric stability has hitherto not been considered with respect to wind turbine sound. However, at the heights that are reached by modern, tall wind turbines the effect has become increasingly important, from an energetic as well as acoustical point of view.

In an earlier paper [2] it has been shown that in a stable atmosphere the sound *level* due to wind turbines is higher than is expected from sound production based on simple logarithmic extrapolation from reference wind speeds. The present paper explores the effect of atmospheric stability on the periodic *level changes* known as 'blade swish'. In the next two sections three possibly relevant effects of a change in atmospheric stability are identified and investigated from a theoretical point of view. All effects result in a higher level of blade swish. Then, in section 4, we will turn to measurement results and show that measured results can be explained by these predicted effects. Finally, in section 5, the results are put in the context of human perception. It can now be understood why in a stable atmosphere (but not in an unstable atmosphere) wind turbine sound is perceived as a fluctuating sound.

## 2. SOURCES OF WIND TURBINE SOUND

There are many publications on the nature and power of turbine sound. See, *e.g.*, the studies by Lowson [3] and Grosveld [4], and the reviews by Hubbard and Shepherd [5] and Wagner *et al* [6]. A short introduction on wind aeroacoustics will be given to elucidate the most important sound producing mechanisms.

If an air flow is smooth around a (streamlined) body, it will generate very little sound. For high speeds and/or over longer lengths the flow in the boundary layer between the body and the main flow becomes turbulent. The rapid turbulent velocity changes at the surface cause sound with frequencies related to the rate of the velocity changes. The turbulent boundary layer at the downstream end of an airfoil produces *trailing edge sound*, which is the dominant audible sound from modern turbines.

As is the case for aircraft wings, the air flow around a wind turbine blade generates lift. An air foil performs best when lift is maximised and drag (flow resistance) is minimised. Both are determined by the angle of attack: the angle ( $\alpha$ ) between the incoming flow and the blade chord (line between front and rear edge; see figure 1). When the angle of attack increases from its optimal value the turbulent boundary layer on the suction (low pressure) side grows in thickness, thereby decreasing power performance and increasing sound level. For high angles of attack this eventually leads to stall, that is: a dramatic reduction in lift.

Apart from this turbulence inherent to an airfoil, the atmosphere itself is turbulent over a wide range of frequencies and sizes. Turbulence can be defined as changes over time and space in wind velocity and direction, resulting in velocity components normal to the airfoil varying with the turbulence frequency causing *in-flow turbulent sound*. Atmospheric turbulence energy has a maximum at a frequency that depends on height and on atmospheric stability. For wind turbine altitudes this peak frequency is of an order of magnitude of once per minute (0.017 Hz). The associated eddy (whirl) scale is of the order of magnitude of several hundreds of meters [7] in an unstable atmosphere, less in a stable atmosphere. Eddy size and turbulence strength decrease at higher frequency, and vanish due to viscous friction when they have reached a size of approximately one millimetre.

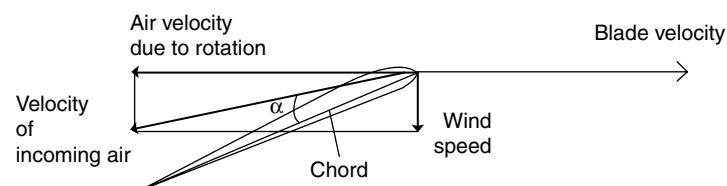


Figure 1 Flow impinging on a turbine blade.

A third sound producing mechanism is the response of the blade to the change in lift when it passes the tower. The wind is slowed down by the tower which changes the angle of attack. The resulting sideways movement of the blade causes *thickness sound* at the blade passing frequency and its harmonics.

A more thorough review of these three sound production mechanisms is given in Appendix I, where frequency ranges and sound levels are quantified in so far as relevant for the present paper. A modern wind turbine sound spectrum can now be divided in (overlapping) regions corresponding to these three mechanisms:

1. Infrasound frequency ( $f < 30$  Hz): the *thickness sound* is tonal, the spectrum containing peaks at the blade passing frequency  $f_B$  and its harmonics.
2. Low frequency: *in-flow turbulent sound* is broad-band noise with a maximum level at approximately 10 Hz and a slope of 3–6 dB per octave.
3. High frequency: *trailing edge (TE) sound* is noise with a maximum level at 500–1000 Hz for the central octave band, decreasing by 11 dB for neighbouring octave bands and more for further octave bands.

Sound originating from the generator or the transmission gear has decreased in level in the past decades and has become irrelevant when considering annoyance for residents. As thickness sound is not relevant for direct perception, turbulent flow is the dominant cause of (audible) sound for modern wind turbines. It is broad-band noise with no tonal components and only a little variation, known as blade swish. Blade swish is sound due to the regular increase in trailing edge sound whenever a blade passes the tower. Trailing edge (TE) sound level is proportional to  $50 \log M$  (see equation A4 in appendix), where  $M$  is the Mach number of the air impinging on the blade. TE sound level therefore increases steeply with blade speed and is highest at the high velocity blade tips. Swish thus originates predominantly at the tips.

Sound from downwind rotors, *i.e.* with the rotor downwind from the tower, was considered problematic as it was perceived as a pulsating sound (see appendix). For modern upwind rotors this variation in sound level is weaker. It is not thought to be relevant for annoyance and considered to become less pronounced with increasing distance due to loss of the effect of directivity, due to relatively high absorption at swish frequencies, and because of the increased masking effect of background noise [8]. However, several effects that increase the level of the swishing sound and are related to increasing atmospheric stability have not been taken into account as yet. Possible effects will be considered before we turn to measurement results.

### 3. EFFECT OF ATMOSPHERIC STABILITY ON WIND TURBINE SOUND

The wind speed  $v_h$  at height  $h$  in the atmosphere can be written as:

$$v_h = v_{\text{ref}} \left( \frac{h}{h_{\text{ref}}} \right)^m \quad (1)$$

where reference height  $h_{\text{ref}}$  is usually 10 m [2, 7]. The relation is suitable where  $h$  is at least several times the roughness length. At high altitudes the wind profile will not follow (1), as eventually a more or less constant wind speed (the geostrophic wind) will be attained. At higher altitudes in a stable atmosphere there may be a *decrease* in wind speed when a nocturnal ‘jet’ develops. The maximum in this jet is caused by a transfer of kinetic energy from the near ground air that decouples from higher air masses as large, thermally induced eddies vanish because of ground cooling. In fact, reversal of the usual near-ground diurnal pattern of low wind speeds at night and higher wind speeds in daytime is a common phenomenon at higher altitudes over land in clear nights [9, 10, 11]. Over large bodies of water the phenomenon may be seasonal as stability occurs more often when the water is relatively cold (winter, spring). This may also be accompanied by a maximum in wind velocity at a higher altitude [12].

In a neutral atmosphere the wind profile can also be modelled with the well known logarithmic or adiabatic profile, where relative wind speed  $v_h/v_{\text{ref}}$  depends on height and surface roughness. This model is widely (and, as yet, only) used in relation to wind turbine sound (see, *e.g.*, [8] or [14]). With regard to wind power

more attention is being paid to stability effects and thus to other wind profile models [see, *e.g.*, 10, 11, 12, 15, 16]. Accurate wind speed profiles can be calculated with a diabatic wind speed model where stability corrections are added to the adiabatic profile (see, *e.g.*, [9] or [13]).

Equation (1) has no theoretical basis, but often provides a good fit to the vertical wind profile, especially when the atmosphere is non-neutral. In flat terrain the stability exponent  $m$  has a value of 0.1 and more. In daytime or in windy nights ( $0.1 < m < 0.2$ ) equation (1) does not deviate much from the logarithmic wind profile: for altitudes up to 100 m and low vegetation (roughness length  $< 10$  cm), wind velocities calculated with equation 1 agree within 20% with the logarithmic wind profile.

For a neutral atmosphere, occurring under heavy clouding and/or in strong winds,  $m$  has a value of approx. 0.2. In an unstable atmosphere -occurring in daytime- thermal effects caused by ground heating are dominant. Then  $m$  has a lower value, down to approx. 0.1. In a stable atmosphere vertical movements are damped because of ground cooling. One would then eventually expect a parabolic wind profile, as is found in laminar flow, corresponding to a value of  $m$  of  $0.7 = \sqrt{1/2}$ . Our measurements near the Rhede wind farm ( $53^\circ 6.2'$  latitude,  $7^\circ 12.6'$  longitude) at the German-Dutch border [2] yielded values of  $m$  up to 0.6. A sample (averages over 0:00–0:30 GMT of each first night of the month in 1973) from data from a 200 m high tower in flat, agricultural land [27] shows that the theoretical value is indeed reached: in ten out of the twelve samples there was a temperature inversion in the lower 120 m, indicating atmospheric stability. In six samples the temperature increased with more than  $1^\circ\text{C}$  from 10 to 120 m height and the exponent  $m$  (calculated from (1):  $m = \log(v_{80}/v_{10})/\log(8)$ ) was 0.43, 0.44, 0.55, 0.58, 0.67 and 0.72. Comparable values have been estimated in the US Midwest [15] and at a Spanish plateau [16]. In the following text we will use a value  $m = 0.15$  for a daytime atmosphere (unstable – neutral),  $m = 0.4$  for a stable, and  $m = 0.65$  for a very stable atmosphere. These values will be used for altitudes between 10 and 120 m.

The magnitude of the effects of increasing stability depends on wind turbine properties such as speed, diameter and height. We will use the dimensions of the wind turbines in the Rhede wind farm, that are typical for a modern 1.5-2 MW wind turbine: hub height 100 m, blade length 35 m and rotational speed increasing with wind speed up to a maximum value of  $\Omega R = 73$  m/s (at 20 rpm).

There are now three factors influencing blade swish level when the atmosphere becomes more stable: a) the higher wind speed gradient, b) the higher wind direction gradient, and c) the relative absence of large scale turbulence.

- a. *Wind speed gradient.* Rotational speed is determined by a rotor averaged wind speed. With increasing atmospheric stability the difference in wind speed between the upper and lower part of the rotor increases. Suppose that the wind speed at hub height is  $v_{100} = 14$  m/s, corresponding to  $v_{10} = 9.8$  m/s in a neutral atmosphere in flat open grass land (roughness length 4 cm). Then in daytime ( $m = 0.15$ ) the wind speed at the lowest point of the rotor would be  $v_{65} = 13.1$  m/s, at the highest point  $v_{135} = 14.6$  m/s. As the blade angle does not change with rotation angle, the difference between the low tip and hub height wind speeds causes a change in angle of attack on the blade of  $\Delta\alpha = 0.8^\circ$  at 20 rpm (see appendix, equation A7). Between the high tip and hub height the change is smaller:  $0.5^\circ$ . In night-time ( $m = 0.4$ ), at the same wind speed at hub height,  $v_{65}$  is 11.8 m/s causing a change in angle of attack at the lower tip relative to hub height of  $1.8^\circ$  (at the high tip:  $v_{135} = 15.8$  m/s,  $\Delta\alpha = 1.5^\circ$ ). When the atmosphere is very stable ( $m = 0.65$ ), wind speed  $v_{65} = 10.5$  m/s and the angle of attack on the low altitude tip deviates  $2.9^\circ$  from the angle at hub height (at the high tip:  $v_{135} = 17.0$  m/s,  $\Delta\alpha = 2.5^\circ$ ).

In fact when the lower tip passes the tower there is a greater mismatch between optimum and actual angle of attack  $\alpha$  because there was already a change in angle of attack related to the wind velocity deficit in front of the tower. For a daytime atmosphere and with respect to the situation at hub height, the change in  $\alpha$  associated to a blade swish level of  $1 \pm 0.5$  dB is estimated as  $2.1 \pm 0.4^\circ$  (see appendix, section C), part of which ( $0.8^\circ$ ) is due to the wind profile and



the rest to the tower. The increase in  $\alpha$  due to the stability related wind profile change must be added to this daytime change in  $\alpha$ . Thus, relative to the daytime (unstable to neutral) atmosphere, the change in angle of attack when the lower tip passes the mast increases with  $1.0^\circ$  in a stable atmosphere, and with  $2.1^\circ$  in a very stable atmosphere. The associated change in trailing edge (TE) sound level, as calculated from equation A6 in the appendix, is  $3.1 \pm 0.7$  dB for a stable and  $5.0 \pm 0.8$  dB for a very stable atmosphere (compared to  $1 \pm 0.5$  dB in daytime). The corresponding total A-weighted sound level will be somewhat less as trailing edge sound is not the only sound source (but it is the dominant source; see section 4C).

At the high tip the change in angle of attack is smaller than for the low tip as there is no (sudden) tower induced change to add to the wind gradient dependent change. The change in angle of attack at the high tip in a very stable atmosphere ( $2.5^\circ$ ) is comparable to the change at the low tip in daytime, and this change is more gradual than for the low tip.

Thus we find that, for  $v_{100} = 14$  m/s, the 1-2 dB daytime blade swish level increases to approx. 5 dB in a very stable atmosphere. The effect is stronger when wind speed increases up to the point where friction turbulence overrides stability and the atmosphere becomes neutral. The increase in trailing edge sound level will be accompanied by a lower peak frequency (see appendix, equation A2). For  $\alpha = 5^\circ$  the shift is one octave.

- b. *Wind direction gradient.* In a stable atmosphere air masses at different altitudes are only coupled by small scale turbulence and are therefore relatively independent. Apart from a higher velocity gradient a higher wind direction gradient is also possible, and with increasing height the wind direction may change significantly. This wind direction shear will change the angle of attack with height. Assuming the wind at hub height to be normal to the rotor, the angle of attack will decrease below and increase above hub height (or vice versa). This effect, however, is small: if we suppose a change in wind direction of  $20^\circ$  over the rotor height at a wind velocity of 10 m/s, the change in angle of attack between extreme tip positions at 20 rpm is only  $0.25^\circ$ , which is negligible relative to the wind velocity shear.
- c. *Less turbulence.* As was shown in an earlier study [2], in areas near a wind farm an increase in blade swish pulse height (The term 'pulse' is used to indicate the upward variation in sound level.) can be explained by the synchronization of two or three pulse trains coming from the two or three closest turbines. In a stable atmosphere wind turbines can run almost synchronously because the absence of large scale turbulence leads to less variation superimposed on the constant (average) wind speed at each turbine. In unstable conditions the average wind speed at both turbines will be equal, but instantaneous local wind speeds will differ because of the presence of large, turbulent eddies at the scale of the inter-turbine distance. In a stable atmosphere the turbulence scale decreases with a factor up to 10, relative to the neutral atmosphere and even more relative to an unstable atmosphere [17]. In stable conditions turbines in a wind farm therefore experience a more similar wind and as a consequence their instantaneous turbine speeds are more nearly equal. This is confirmed by long term measurements by Nanahara *et al.* [18] who analysed coherence of wind speeds between different locations in two coastal areas. At night wind speeds at different locations were found to change more coherently than they did at daytime [19]. The difference between night and day was not very strong, probably because time of day on its own is not a sufficient indicator for stability. The decay of coherence was however strongly correlated with turbulence intensity, which in turn is closely correlated to stability. (In a coastal location atmospheric stability also depends on wind direction as landwards stability is a diurnal, but seawards a seasonal phenomenon. Also, a fixed duration for all nights in a year does not coincide with the time that the surface cools (between sundown and sunrise), which is a prerequisite for stability.)

Near the Rhede wind farm we found that, because of the *near*-synchronicity of several turbines, sometimes two or three were in phase and the blade passing pulses coincided, and then went out of phase again [2]. This would lead to a doubling (+3 dB) or tripling (+5 dB) of pulse height. If in a (very) stable atmosphere individual swish pulse heights are 3–5 dB (see section 3a above), synchronicity at the Rhede wind farm or similar configurations would thus lead to pulse heights of 6–10 dB.

Synchronicity here refers to the sound pulses from the different turbines as observed at the location of the observer. So, pulses synchronise when they arrive simultaneously. This is determined by differences in phase (rotor position) between turbines and in propagation distances of the sound from the turbines. Phase differences between turbine rotors occur because turbines are not connected and because of differences in actual performance. The place where synchronicity is observed will change when the phase difference between turbines changes. With exact synchronicity there would be a fixed interference pattern, with synchronicity at fixed spots. Because of near-synchronicity however, synchronicity will change over time and place and an observer will hear coinciding pulses for part of the time only.

A second effect of the decrease in turbulence strength is that in-flow turbulent sound level also decreases. The resulting decrease in broad band sound level lowers the minimum in the temporal variations, thereby increasing modulation depth.

We conclude that the higher wind speed gradient and (near-) synchronicity increase blade swish levels at some distance from a wind farm. The higher infrasound level due to extra blade loading is not perceptible because of the high hearing threshold at the very low blade passing frequency. However, the effect of added boundary layer turbulence on the blade increases the levels at the higher frequencies that already were dominating the most audible part of the sound. Near a wind farm the variation in sound level will depend on the distances of the wind turbines relative to the observer: the level increase due to several turbines will reach higher levels when more turbines are at approximately equal distances and thus contribute equal immission levels. The increase in level variation, or beating, is thus at well-audible frequencies and has a repetition rate equal to the blade passing frequency.

Thus, theoretically it can be concluded that in stable conditions (low ambient sound level, high turbine sound power and higher modulation or swish level) wind turbine sound can be heard at greater distances and is of lower frequency due to absorption and the frequency shift of swish sound. It is thus a louder and more low-frequency ‘thumping’ sound and less the swishing sound than observed close to a daytime wind turbine.

## 4. MEASUREMENT RESULTS

### 4.1. Locations

In the summers of 2002 and 2004 wind turbine sounds have been recorded in and near the Rhede wind farm on the German-Dutch border. The farm (figure 2) has a straight south to north row of ten turbines at approximately 300 m intervals, running parallel to the border, and seven less regularly spaced turbines east of the straight row. Each turbine is 98 m to the hub height, and has a blade length of 35 m, and produces nominally 1.8 MW electric power.

The measurement location at dwelling R is west of the turbines, 625 m from the nearest turbine. The microphone position was at 4 m height and close to the house, but with no reflections except from the ground. The measurement location at dwelling P, 870 m south of R, was 1.5 m above a paved terrace in front of the façade of the dwelling at 750 m distance from the nearest turbine. The entire area is quiet, flat, agricultural land with some trees close to the dwellings. There is little traffic and there are no significant permanent human sound sources.

A third dwelling Z is in Boazum in the northern part of the Netherlands, 280 m west of a single, two-speed turbine (45 m hub height, 23 m blade length, 20/26 rpm). The area is again quiet, flat and agricultural. The immission measurement point is at 1.5 m height above gravel near the dwelling. This measurement site is included here to show that the influence of stability on blade swish levels occurs also with

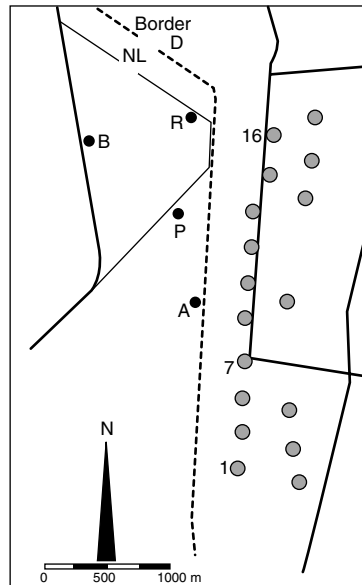


Figure 2 Turbines (grey circles) in and measurement locations (A,B,P,R) near the Rhede wind farm; solid lines are roads.

**Table I. Overview of measurement locations and times and of turbine speed and wind**

Location	Measurement		Turbine speed (rpm)	Wind speed (m/s)		Wind direction (° north)
	Date	Time		$v_{10}$	$v_{hub}$	
Dwelling P	June 3, 2002	00:45	20	5	14	100
Turbine 7	June 3, 2002	06:30	19	5	15	100
Turbine I	June 3, 2002	06:45	19	5	15	100
Dwelling R	Sep. 9, 2004	23:07	18	4	14	80
Turbine 16						
Dwelling Z	Oct. 18, 2003	01:43	26	3	6	60

smaller, single turbines. At all locations near dwellings the microphone was fitted in a 9 cm diameter foam wind screen.

Table I gives an overview of measurement (start) times and dates of observed turbine speeds and of wind speed and direction, for situations for which results will be given below. The wind speed at hub height  $v_{hub}$  has been determined from turbine rotation speed  $N$  or sound power level  $L_w$  ([2], the relation  $v_{hub} - N$  follows from ref. 3 and 11 in [1]). The wind speed  $v_{10}$  at 10 m height was continuously measured at or near location A, except for location Z, where data from several meteorological stations were used showing that the wind was similar and nearly constant in the entire northern part of the Netherlands. In all cases there were no significant variations in wind speed at the time of measurement. Wind speed at the microphone was lower than  $v_{10}$  because of the low microphone height and shelter provided by trees nearby. Wind direction is given in degrees relative to north and clockwise (90° is east). The spectra near a turbine were measured with the microphone just above a hard surface at ground level 100 m downwind of a turbine in compliance with IEC 61400 [14] as much as possible (non-compliance did not lead to differences in result [2]; for reasons of non-compliance, see [34]). The levels plotted are immission levels: measured  $Leq$  minus 6 dB correction for coherent reflection against the hard surface [16]. The plotted levels near the dwellings are also immission levels: measured  $Leq$  minus 3 dB correction for incoherent reflection at the façade for dwelling P, or measured  $Leq$  without any correction for dwellings R and Z.



At dwelling P at the time of measurement the beat in the turbine sound was very pronounced. In the other measurements (dwellings R and Z) the beating was not as loud. The measurements near turbine 16 and dwelling R at 23:07 on September 9 were performed simultaneously.

### 4.2. Frequency response of instruments

For the Rhede measurements sound was recorded on a TASCAM DA-1 DAT-recorder with a precision 1 in Sennheiser MKH 20 P48 microphone. The sound was then sampled in 1-second intervals on a Larson Davis 2800 frequency analyser. From 1 to 10 000 Hz the frequency response of the DAT-recorder and LD2800 analyser have been determined with a pure tone electrical signal as input. The LD2800 response is flat ( $\pm 1$  dB) for all frequencies. The DAT-recorder is a first order high pass filter with a corner frequency of 2 Hz. The frequency response of the microphone was of most influence and has been determined relative to a B&K  $\frac{1}{2}$  in microphone type 4189 with a known frequency response [20]. Equivalent spectral sound levels with both microphones in the same sound field (approx. 10 cm mutual distance) were compared. For frequencies of 2 Hz and above the entire measurement chain is within 3 dB equivalent to a series of two high pass filters with corner frequencies of  $f_1 = 4$  Hz and  $f_2 = 9$  Hz, or a transfer function equal to  $-20 \log[1 + (f_1/f)^2] - 20 \log[1 + (f_2/f)^2]$ . For frequencies below 2 Hz this leads to high signal reductions ( $< -40$  dB) and consequentially low signal to (system) noise ratios. Therefore values at frequencies  $< 2$  Hz are not presented.

For the Boazum measurements sound was recorded on a Sharp MD-MT99 mini-disc recorder with a 1 in Sennheiser ME62 microphone. The frequency response of this measurement chain is not known, but is assumed to be flat in the usual audio frequency range. Simultaneous measurements of the broad band A-weighted sound level were done with a precision (type 1) sound level meter. Absolute precision is not required here as the minidisc recorded spectra are only used to demonstrate relative spectral levels. Because of the ATRAC time coding of a signal, a minidisc recording does not accurately follow a level change in a time interval  $< 11.6$  ms. This is insignificant in the present case as the 'fast' response time of a sound level meter is much slower (125 ms).

### 4.3. Measured Emission and Immission Spectra

Recordings were made at evening, night or early morning. On June 3, 2002, sound was recorded at dwelling P at around midnight and early in the morning near two turbines (numbers 1 and 7). At P at these times a distinct beat was audible in the wind turbine sound. In figure 3,  $\frac{1}{3}$  octave band spectra of the recorded sound at P and at both turbines have been plotted. In each figure A, B and C, 200 sound pressure spectra sampled in one-second intervals, as well as the energy averaged spectrum of the 200 samples have been plotted. The standard deviation of  $\frac{1}{3}$  octave band levels is typically 7 dB at very low frequencies, decreasing to approx. 1 dB at 1 kHz. The correlation coefficient  $\rho$  between all unweighted  $\frac{1}{3}$  octave band levels and the overall A-weighted sound level has also been plotted for each  $\frac{1}{3}$  octave band frequency.

For frequencies below approximately 10 Hz the sound is dominated by the thickness sound associated with the blade passing frequency and harmonics. In the rest of the infrasound region and upwards, in-flow turbulence is the dominant sound producing mechanism. Gradually, at frequencies above 100 Hz, trailing edge sound becomes the most dominant source, declining at high frequencies of one to several kHz. Trailing edge sound is more pronounced at turbine 1 (T1) compared to turbine 7 (T7), causing a hump near 1000 Hz in the T1 spectra. At very high frequencies ( $> 2$  kHz) sometimes higher spectral levels occur due to birds.

It is clear from the spectra that most energy is found at lower frequencies. However, most of this sound is not perceptible. To assess the infrasound level relevant to human perception it can be expressed as a G-weighted level [30]. With G-weighting sound above the infrasound range is suppressed. The average infrasound perception threshold is 95 dB(G) [28]. The measured G-weighted levels are 15-20 dB below this threshold: 80.5 and 81.1 dB(G) near turbines 1 and 7 respectively, and 76.4 dB(G) at the façade.

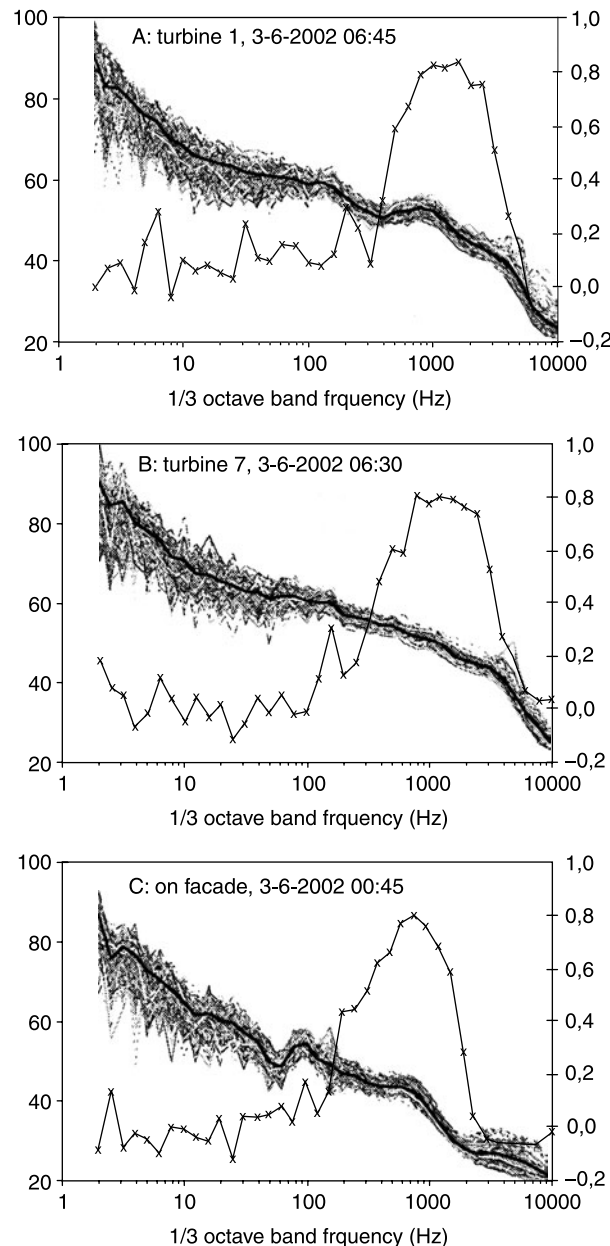


Figure 3 Left axis (in dB): 200 consecutive, unweighted and 1 second spaced 1/3 octave band levels (thin lines), and average spectral level (thick line) near turbines 1 and 7, and near dwelling P; right axis: coefficient of correlation (line with markers) at each 1/3 octave band frequency between all 200 1/3 octave band levels and overall A-weighted levels.

The correlations show that variations in total A-weighted level near the turbines are correlated with the 1/3 octave band levels with frequencies from 400 through 3150 Hz (where  $\rho > 0.4$ ), which is trailing edge sound. This is one octave lower (200 - 1600 Hz) for the sound at the façade: the higher frequencies were better absorbed during propagation through the atmosphere.

The façade spectra in figure 3C show a local minimum at 50-63 Hz, followed by a local maximum at 80-100 Hz. (In a FFT spectrum minima are at 57 and 170 Hz, maxima at 110 and 220 Hz.) This is caused by interference between the direct sound wave and the wave reflected by the façade at 1.5 m from the microphone: for wave lengths of approx. 6 m (55 Hz) this leads to destructive interference, for wave lengths of 3 m (110 Hz) to constructive interference.

In figure 4A the three average spectra at the same locations as in figure 3A-C have been plotted, but now for a total measurement time of approx. 9.5 (façade),

## The Effect of Atmospheric Stability on Low Frequency Modulated Sound

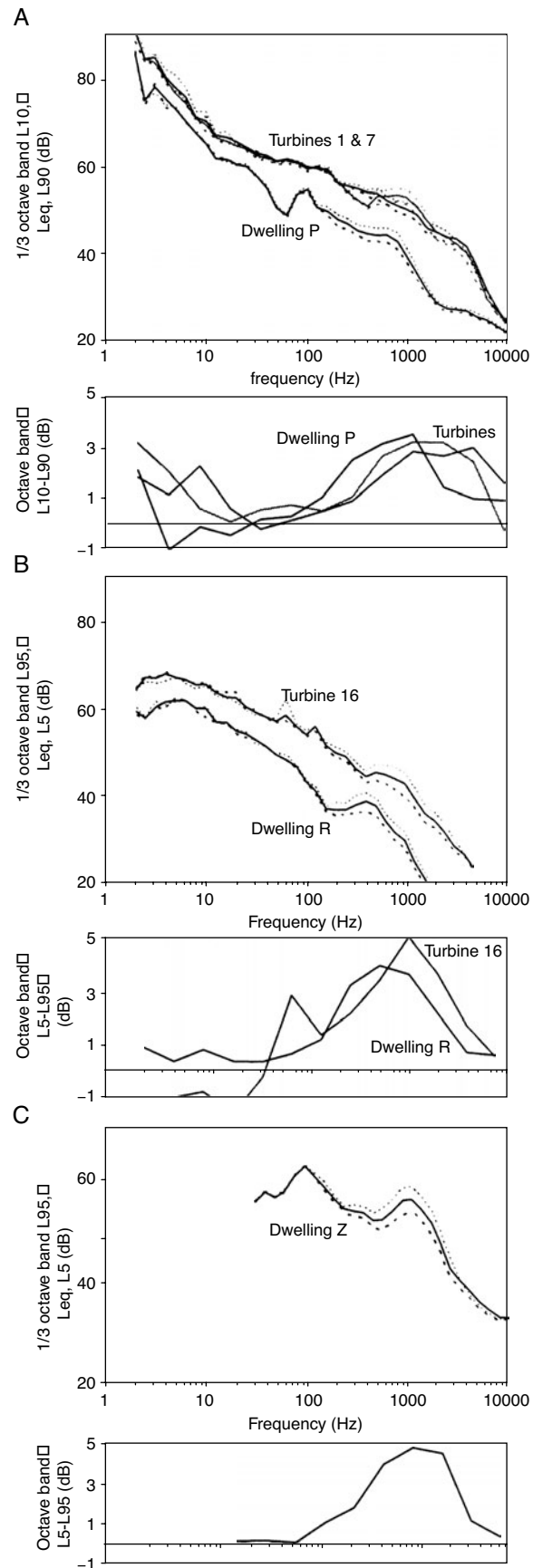


Figure 4

Upper panels A,B,C: 1/3 octave band Leq near windturbines and dwellings (thick lines) and Leq of all samples with resp. 5% highest (thin dotted lines) and 5% lowest values of broad band  $L_A$  (thick dotted lines). Lower panels: difference between Leq of 5- and 95-percentile octave band levels.

5 (T7) and 6 (T1) minutes. For each of these measurement periods the average of the 5% of samples with the highest broad band A-weighted sound level (*i.e.* the equivalent spectral level of the  $L_{A5}$  percentile) has also been plotted, as well as the 5% of samples with the lowest broad band level ( $L_{A95}$ ). The range in A-weighted broad band level can be defined as the difference between the highest and lowest value:  $R_{bb} = L_{Amax} - L_{Amin}$ . Similarly the range per 1/3 octave or octave band  $R_f$  can be defined by the difference in spectral levels corresponding to  $L_{Amax}$  and  $L_{Amin}$ . The difference between  $L_{A5}$  and  $L_{A95}$  is a more stable value, avoiding possibly incidental extreme values, especially when spectral data are used.  $R_{bb,90}$  is defined as the difference in level between the 5% highest and the 5% lowest broad band sound levels:  $R_{bb,90} = L_{A5} - L_{A95}$ . For spectral data,  $R_{f,90}$  is the difference between spectral levels associated with  $L_{A5}$  and  $L_{A95}$ . Values of  $R_{f,90}$  are plotted in the lower part of figure 4A (here octave band levels have been used to avoid the somewhat ‘jumpy’ behaviour of the 1/3 octave band levels). Close to turbines 1 and 7  $R_{bb}$  is 4.8 and 4.1 dB, respectively.  $R_{bb,90}$  is 3.2 and 2.6 dB, which is almost the same as  $R_{f,90}$  (3.2 and 3.0 dB) at 1000–4000 Hz. Further away, at the façade,  $R_{bb}$  is comparable to the near turbine values: 4.9 dB.  $R_{bb,90}$  at the façade is 3.3 dB and again almost the same as maximum  $R_{f,90}$  (3.5 dB) at 1000 Hz.

Also, close to the turbine there is a low frequency maximum in  $R_{f,90}$  at 2 (or 8) Hz that is also present at the façade, indicating that the modulation of trailing edge sound is correlated in time with the infrasound caused by the blade movement.

Figure 4B presents similar plots for the average spectra and the  $L_{A5}$  and  $L_{A95}$  spectra at dwelling R and near turbine T16 over a period of 16 minutes. Close to the turbine the broadband  $R_{bb,90}$  is 3.7 dB; octave band  $R_{f,90}$  is highest (5.1 dB) at 1000 Hz. Near R broadband  $R_{bb,90}$  is also 3.7 dB, and octave band  $R_{f,90}$  is highest (4.0 dB) at 500 Hz. The  $R_{bb}$  ranges are 2.3–2.5 dB higher than the 90% ranges  $R_{bb,90}$ . A 25 second part of this 16 min period is shown in figure 5. The broad band level  $L_A$  changes with time at T16 and R, showing a more or less regular variation with a period of approximately 1 s ( $= 1/f_b$ ). In these measurements the infrasound level was lower than in the previous measurements at dwelling P where beating was more pronounced. G-weighted sound level during the 16 minutes at R was 70.4 dB(G), and at T16 77.1 dB(G).

Finally figure 3C gives average spectra over a period of 16 minutes at dwelling Z.  $R_{f,90}$  is now highest (4.8 dB) at 1 kHz, and broadband  $R_{bb,90}$  is 4.3 dB ( $R_{bb} = 5.9$  dB). The turbine near Z is smaller and lower, but rotates faster than the Rhede turbines; for a hub height wind speed of 6 m/s the expected calculated increase in trailing edge sound for the lower tip relative to the day time situation is  $2.0 \pm 0.8$  dB for

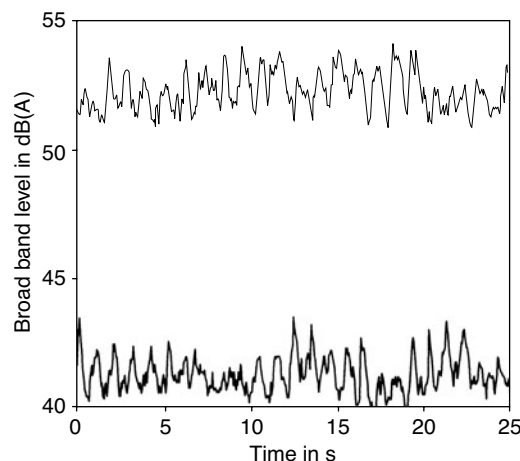


Figure 5 Broad band A-weighted immission sound level near turbine T16 (upper plot) and close to dwelling R (lower plot).

a stable, and  $2.9 \pm 0.8$  dB for a very stable atmosphere. For this turbine a peak trailing edge sound level is expected (according to equation A2 in appendix) at a frequency of  $1550/\alpha \text{ Hz} \approx 400 - 800 \text{ Hz}$ .

In all cases above the measured sound includes ambient background sound. Ambient background sound level could not be determined separately at the same locations because the wind turbine(s) could not be stopped (it has been shown elsewhere that it is a flaw in noise regulation to make independent noise assessment procedurally impossible because of its dependency on wind turbine owner's consent [34]). However, at audible frequencies it could be ascertained by ear that wind turbine sound was dominant. At infrasound frequencies this could not be ascertained. But if significant ambient sound were present, subtracting it from the measured levels would lead to lower (infrasound) sound levels, which would not change the conclusion, based on the G-weighted level, that measured infrasound must be considered inaudible.

#### 4.4. Beats Caused by Interaction of Several Wind Turbines

In the previous section we saw that measured variations in broad band sound level ( $R_{bb}$ ) were 4 to 6 dB. Figure 6 presents the time variation of the broad band A-weighted level from the sound level at the façade of dwelling P over a one minute period [2]. In this night stable conditions prevailed ( $m = 0.45$  from the wind speeds in table I). Turbines 12 and 11 are closest at 710 and 750 m, followed by turbines 9 and 14 at 880 and 910 m. Other turbines are more than 1 km distant and have an at least 4 dB lower immission level than the closest turbine has. The sequence in figure 6 begins when the turbine sound is noisy and constant within 2 dB. After some time (at  $t = 155$  s) regular pulses appear with a maximum height of 3 dB, followed by a short period with louder (5 dB) and steeper (rise time up to 23 dB/s) pulses. The pulse frequency is equal to the blade passing frequency. Then ( $t > 180$  s) the pulses become weaker and there is a light increase in wind speed.

This was one of the nights where a distinct beat was audible: a period with a distinct beat alternating with a period with a weaker or no beat, repeated more or less during the entire night. The pattern is consistent with three pulse trains of slightly different frequencies [2].

In figure 7 the equivalent 1/3 octave band spectrum at the façade of P has been plotted for the period of the beat ( $165 < t < 175$  s in figure 6, spectra sampled at a rate of  $20 \text{ s}^{-1}$ ), as well as the equivalent spectrum associated with the 5% highest ( $L_{A5} = 52.3 \text{ dB(A)}$ ) and the 5% lowest ( $L_{A95} = 47.7 \text{ dB(A)}$ ) broad band levels and the difference between both. As in the similar spectra in figure 4 we see that the beat corresponds to an increase at frequencies where trailing edge sound dominates: the sound pulses correspond to 1/3 octave band levels between 200 and 1250 Hz and are highest at 800 Hz. In figure 7 also the equivalent 1/3 octave band levels are plotted for the period after beating where the wind was picking up slightly ( $t > 175$  s in figure 6). Here spectral levels above 400 Hz are the same or slightly lower as on average at the time of beating, but at lower frequencies down to 80 Hz (related to in-flow turbulence) levels now are 1 to 2 dB higher. The increase in the 'more wind' spectrum at high frequencies ( $> 2000 \text{ Hz}$ ) is probably from rustling tree leaves.

Figure 8 shows sound spectra for a period with a distinct beat ( $150 < t < 175$  s in figure 6), and a period with a weak or no beat ( $130 < t < 150$  s). Each spectrum is

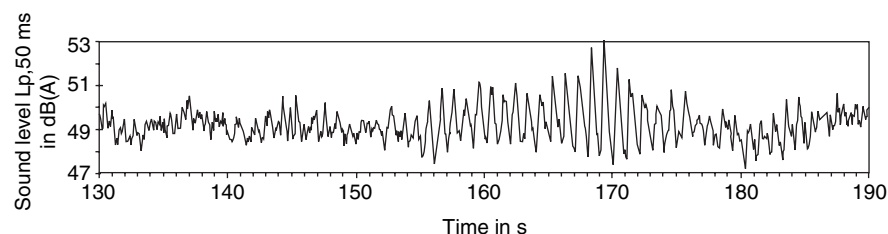


Figure 6 Broad band A-weighted immission sound level at façade of dwelling P.

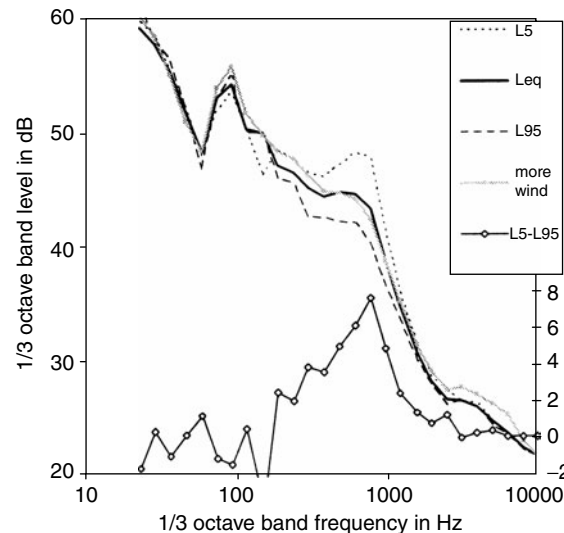


Figure 7 1/3 octave band levels at façade of dwelling P during beating ( $L_{eq}$ ,  $L_{10}$  and  $L_{90}$ ) and when wind speed is picking up ( $L_{eq}$ ).

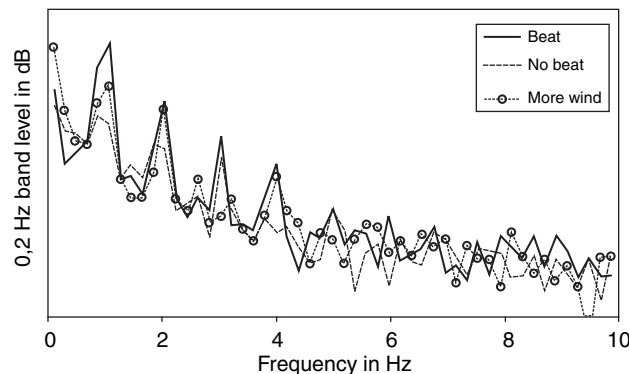


Figure 8 Sound power spectrum of A-weighted broad band immission sound level at façade of dwelling P when beating is distinctly or not audible and with slightly increased wind speed.

an FFT of 0.2 Hz line width from broad band A-weighted immission sound pressure level values. The frequencies are therefore *modulation*, not sound frequencies. The abscissa spans 20 dB. The spectra show that distinct beating is associated with higher total A-weighted levels at the blade passing frequency and its harmonics. As has been shown above, the higher level is related to the frequency range of trailing edge sound, not to infrasound frequencies linked to thickness sound. When beating is weaker but there is more wind ( $t > 175$  s), the level of the odd harmonics (base frequency  $k = 1$ , and  $k = 3$ ) is lower than during ‘beat’, whereas the first two even harmonics ( $k = 2, 4$ ) are equally loud, indicating more distorted (less sinusoidal) and lower level pulses. It is important to realize that the periodic variation as represented in figure 8 is the result from a wind farm, not from a single turbine.

In long term measurements near the Rhede wind farm, where average and percentile sound levels were determined over 5 minute periods, periods where wind turbine sound was dominant could be selected with a criterion ( $R_{bb,90} = L_{A5} - L_{A95} \leq 4$  dB) implying a fairly constant source with less than 4 dB variation for 90% of the time [2]. The statistical distribution of the criterion values has been plotted in 1 dB intervals in figure 9 for the two long term measurement locations A and B (see figure 2). Total measurement times –with levels in compliance with the criterion– were 110 and 135 hours, respectively. Relative to dwellings P and R, one location (A, 400 m from nearest turbine) is closer to the turbines, the other (B, 1500 m) is further. The figure



## The Effect of Atmospheric Stability on Low Frequency Modulated Sound

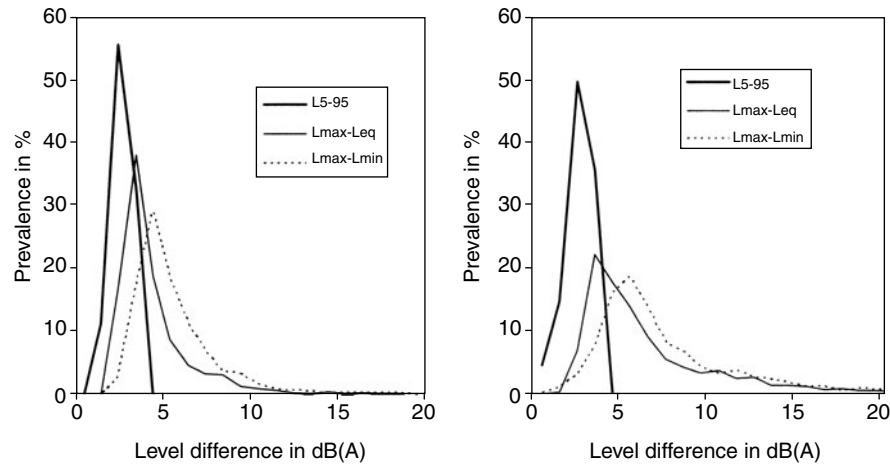


Figure 9 Statistical distribution of level differences (in 1 dB-classes) between high and low sound levels within 5 minute periods at 400 m (left) and 1500 m (right) from the nearest wind turbine.

shows that the criterion value (cut off at 4 dB) at both locations peaks at 2.5 dB. Also plotted in figure 9 is the value of  $L_{Amax} - L_{Aeq}$  (while  $R_{bb,90} \leq 4$  dB), peaking at 3.5 dB at both locations. Finally, the difference between maximum and minimum level within 5 minute periods,  $L_{Amax} - L_{Amin} = R_{bb}$ , peaks at 4.5 dB (location A) and 5.5 dB (B). Where  $R_{bb} > 7$  dB, the distributions are influenced by louder (non-turbine) sounds, such as from birds. Extrapolation of the distribution from lower values suggests that the maximum range  $R_{bb}$  due to the wind farm is 8.5 dB (location A) to 9.5 dB (B). This is 4 dB more than the most frequently occurring ranges at both locations.

### 4.5. Summary of Results

In table II the level variations due to blade swish as determined in the previous sections have been summarised. Some values not presented in the text have been added. The ranges are presented as  $R_{bb}$  and  $R_{bb,90}$ . The latter is of course a lower value as it leaves out high and low excursions occurring less than 10% of the time. The time interval over which these level differences occur differ: from several up to 16 minutes for the short term measurements, where wind conditions can be presumed constant, up to over 100 hours at locations A and B.

## 5. PERCEPTION OF WIND TURBINE SOUND

In a review of literature on wind turbine sound Pedersen concluded that wind turbine noise was not studied in sufficient detail to be able to draw general conclusions, but that the available studies indicated that at relatively low levels wind turbine sound was more annoying than other sources of community noise such as traffic [21]. In a field study by Pedersen and Persson Waye [22] 8 of 40 respondents living in dwellings with (calculated) maximum outdoor immission levels of 37.5 - 40.0 dB(A) were very annoyed by the sound, and at levels above 40 dB(A) 9 of 25 respondents were very annoyed. The correlation between sound level (in 2.5 dB classes) and annoyance was significant ( $p < 0.001$ ). In this field study annoyance was correlated to descriptions of the sound characteristics, most strongly to swishing with a correlation coefficient of 0.72 [22]. A high degree of annoyance is not expected at levels below 40 dB(A), unless the sound has special features such as a low-frequency components or an intermittent character [23]. Psychoacoustic characteristics of wind turbine sound have been investigated by Persson-Waye *et al.* in a laboratory setting with naive listeners (students not used to wind turbine sound): the most annoying sound recorded from five different turbines were described as 'swishing', 'lapping' and 'whistling', the least annoying as 'grinding' and 'low frequency' [24]. People living close to wind turbines, interviewed by Pedersen *et al.*, felt irritated

**Table II. Level variation in modern wind turbine<sup>1</sup> sound due to blade swish, in dB**

Location		Reference	Atmospheric condition	$R_{bb}$ $L_{Amax} - L_{Amin}$	$R_{bb,90}$ $L_{A5} - L_{A95}$
<b>Calculated results</b>					
Single turbine		Section 3a	neutral	$1.5 \pm 0.5$	
		Section 3a	stable	$3.1 \pm 0.7$	
		Section 3a	very stable	$5.0 \pm 0.8$	
Two turbines			(very) stable	single + 3	
<b>Measured results</b>					
Single turbine		[8]	unspecified	< 3	
Single turbine	Near T1	fig. 2A		4.8	3.2
	Near T7	fig. 2A		4.1	2.6
	Near T16	fig. 2B		6.0	3.7
Multiple turbines	dwelling Z	fig. 2C	stable	5.9 <sup>2</sup>	4.3
	dwelling R	fig. 2B		6.2	3.7
	façade dwelling P	fig. 2A		4.9	3.3
	façade P + beat	fig. 5		5.4	
	Location A	fig. 6A		4.5 (most frequent)	
				8.5 (maximum)	
			long term, stable		
	Location B	fig. 6B		5.5 (most frequent)	
				9.5 (maximum)	

notes:

<sup>1</sup>hub height 100 m, rotor diameter 70 m, 20 rpm<sup>2</sup>for this turbine (hub height 45 m, diameter 46 m, 26 rpm)  $R_{bb} < 3.7$  dB was calculated

because of the intrusion of the wind turbines in their homes and gardens, especially the swishing sound, the blinking shadows and constant rotation [25].

Our experience at distances of approx. 700 to 1500 m from the Rhede wind farm, with the turbines rotating at high speed in a clear night and pronounced beating audible, is that the sound resembles distant pile driving. When asked to describe the sound of the turbines in this wind farm, a resident compares it to the surf on a rocky coast. Another resident near a set of smaller wind turbines, likens the sound to that of a racing rowing boat (where rowers simultaneously draw, also creating a periodic swish). Several residents near single wind turbines remark that the sound often changing to clapping, thumping or beating when night falls: 'like a washing machine'. It is common in all descriptions that there is noise ('like a nearby motorway', 'a B747 constantly taking off') with a periodic increase superimposed. In all cases the sound acquires this more striking character late in the afternoon or at night, especially in clear nights and downwind from a turbine.

Part of the relatively high annoyance level and the characterisation of wind turbine sound as lapping, swishing, clapping or beating may be explained by the increased fluctuation of the sound [2, 21]. Our results in table 2 show that in a stable atmosphere measured fluctuation levels are 4 to 6 dB for single turbines, and in long term measurements (over many 5 minute periods) near the Rhede wind farm fluctuation levels of approx. 5 dB are common but may reach values up to 9 dB.

## The Effect of Atmospheric Stability on Low Frequency Modulated Sound

The level difference associated with an amplitude modulation (AM) factor  $mf$  is  $\Delta L = 20 \log((1+mf)/(1-mf))$ . The modulation factor  $mf$  is the change in sound pressure amplitude due to modulation, relative to the average amplitude. For  $\Delta L < 9$  dB a good approximation ( $\pm 5\%$ ) is  $mf = 0.055 \Delta L$ . Now when  $\Delta L$  rises from 3 dB, presumably a maximum value for a daytime (unstable or neutral) atmosphere, to 6 dB,  $mf$  rises from 17% to 33%. For a maximum value of  $\Delta L = 9$  dB,  $mf$  is 50%.

Fluctuations are perceived as such when the modulation frequencies are less than 20 Hz. Human sensitivity for fluctuations is highest at  $f_{\text{mod}} = 4$  Hz, which is the frequency typical for rhythm in music and speech [26], and for frequencies of the modulated sound close to 1 kHz. For wind turbines we found that a typical modulation frequency is 1 Hz, modulating the trailing edge sound that itself is at frequencies of 500 – 1000 Hz. So human sensitivity for wind turbine sound fluctuations is relatively high.

Fluctuation strength can be expressed in a percentage relative to the highest perceptible fluctuation strength (100%) or in the unit vacil [26]. The reference value for the absolute fluctuation strength is 1 vacil, equalling a 60 dB, 1 kHz tone, 100% amplitude-modulated at 4 Hz [26].

For an AM pure tone as well as AM broad band noise, absolute fluctuations strength is zero until  $\Delta L \approx 3$  dB, then increases approximately linearly with modulation depth for values up to 1 vacil. For a broad band noise level  $L_A$  the fluctuation strength  $F_{\text{bb}}$  can be written as [26]:

$$F_{\text{bb}} = \frac{5.8(1.25 mf - 0.25)(0.05 L_A - 1)}{(f_{\text{mod}}/5\text{Hz})^2 + (4\text{Hz}/f_{\text{mod}}) + 1.5} \quad \text{vacil} \quad (2)$$

With typical values of  $f_{\text{mod}} = 1$  Hz and  $L_A = 40$  dB(A), this can be written as  $F_{\text{bb}} = 1.31(mf-0.2)$  vacil or, when  $\Delta L < 9$  dB:

$$F_{\text{bb}} = 0.072(\Delta L - 3.6) \quad \text{vacil} \quad (3)$$

When  $\Delta L$  increases from 3 to 6 dB,  $F_{\text{bb}}$  increases from negligible to 0.18 vacil. For the high fluctuation levels found at locations A and B ( $\Delta L = 8 - 9$  dB),  $F_{\text{bb}}$  is 0.32 to 0.39 vacil.

It can be concluded that, in a stable atmosphere, the fluctuations in modern wind turbine sound can be readily perceived. However, as yet it is not clear how this relates to possible annoyance. It can however be likened to the rhythmic beat of music: pleasant when the music is appreciated, but distinctly intrusive when the music is unwanted.

The hypothesis that these fluctuations are important, is supported by descriptions of the character of wind turbine sound as ‘lapping’, ‘swishing’, ‘clapping’, ‘beating’ or ‘like the surf’. Those who visit a wind turbine in daytime will usually not hear this and probably not realise that the sound can be rather different in conditions that do not occur in daytime. This may add to the frustration of residents: “Being highly affected by the wind turbines was hard to explain to people who have not had the experiences themselves and the informants felt that they were *not being believed*” [25]. Persson-Waye *et al.* observed that, from five recorded different turbine sounds “the more annoying noises were also paid attention to for a longer time”. This supported the hypothesis that awareness of the noise and possibly the degree of annoyance depended on the content (of intrusive character) of the sound [24].

Fluctuations with peak levels of 3 – 9 dB above a constant level may have effects on sleep quality. The Dutch Health Council [33] states that “at a given  $L_{\text{night}}$  value, the most unfavourable situation in terms of a particular direct biological effect of night-time noise is not, as might be supposed, one characterised by a few loud noise events per night. Rather, the worst scenario involves a number of noise events all of which are roughly 5 dB(A) above the threshold for the effect in question.” For transportation noise (road, rail, air traffic) the threshold for motility (movement), a direct biological effect having a negative impact on sleep quality, is a sound exposure level per sound event of  $\text{SEL} = 40$  dB(A) in the bedroom [33]. The pulses in figure 6

have SEL-values up to 50 dB(A), but were measured on the façade. With an open window facing the wind turbines indoor SEL-values may exceed the threshold level. In other situations this of course depends on distance to and sound power of the turbines and on the attenuation between façade and bedroom. It is not clear whether the constant and relatively rapid repetition of wind turbine sound beats will have more or less effect on sleep quality, compared to vehicle or airplane passages. Pedersen and Persson Waye found that at dwellings where the (outdoor) sound level due to wind turbines exceeded 35 dB(A), 16% of 128 respondents reported sleep disturbance by this sound, of whom all but two slept with a window open in summer [22].

## 6. DISCUSSION AND CONCLUSION

Atmospheric stability has a significant effect on wind turbine sound, especially for modern, tall turbines.

First, it is related to a change in wind profile causing strong, higher altitude, winds while at the same time wind close to the ground may become relatively weak. High sound immission levels may thus occur at low ambient sound levels, a fact that has not been recognised in noise assessments where a neutral or unstable atmosphere is usually implied. As a result, wind turbine sound that is masked by ambient wind-related sound in daytime, may not be masked at night time. This has been dealt with elsewhere [2].

Secondly, the change in wind profile causes a change in angle of attack on the turbine blades. This increases the thickness (infra) sound level as well as the level of trailing edge (TE) sound, especially when a blade passes the tower. TE sound is modulated at the blade passing frequency, but it is a high frequency sound, well audible and indeed the most dominant component of wind turbine noise. The periodic increase in sound level when the blade passes the turbine tower, blade swish, is a well known phenomenon. Less well known is the fact that increasing atmospheric stability creates greater changes in the angle of attack over the rotor plane that add up with the change near the tower. This results in a thicker turbulent TE boundary layer, in turn causing a higher swish level and a shift to somewhat lower frequencies. It can be shown theoretically that for a modern, tall wind turbine in flat, open land the angle of attack at the blade tip passing the tower changes by approx.  $2^\circ$  in daytime, but this value increases by  $2^\circ$  when the atmosphere becomes very stable. The calculated rise in sound level during swish then increases from 1–2 dB to 4–6 dB. This value is confirmed by measurements at single turbines in the Rhede wind farm where maximum sound levels rise 4 to 6 dB above minimum sound levels within short periods of time.

Thirdly, atmospheric stability involves a decrease in large scale turbulence. Large fluctuations in wind speed (at the scale of a turbine) vanish, and the coherence in wind speed over distances as great as or larger than the size of an entire wind farm increases. As a result turbines in the farm are exposed to a more constant wind and rotate at a more similar speed with less fluctuations. Because of the near-synchronicity, blade swishes may arrive simultaneously for a period of time and increase swish level. The phase difference between turbines determines where this amplification occurs: whether the swish pulses will coincide at a location depends on this phase difference and the propagation time of the sound. In an area where two or more turbines are comparably loud the place where this amplification occurs will sweep over the area with a velocity determined by the difference in rotational frequency. The magnitude of this effect thus depends on stability, but also on the number of wind turbines and the distances to the observer. This effect is in contrast to what was expected, as it seemed reasonable to suppose that turbines would behave independently and thus the blade swish pulses from several turbines would arrive at random, resulting in an even more constant level than from one turbine. Also, *within* a wind farm the effect may not be noticed, since comparable positions in relation to two or more turbines are less easily realised at close distances.

Sound level differences  $L_{Amax} - L_{Amin}$  (corresponding to swish pulse heights) within 5 minute periods over long measurement periods near the Rhede wind farm show that level changes of approximately 5 dB occur for an appreciable amount of time and may

less often be as high as 8 or 9 dB. This level difference did not decrease with distance, but even increased 1 dB when distance to the wind farm rose from 400 m to 1500 m. The added 3-5 dB, relative to a single turbine, is in agreement with simultaneously arriving pulses from two or three approximately equally loud turbines.

The increase in blade swish level creates a new percept, fluctuating sound, that is absent or weak in neutral or unstable atmospheric conditions. Blade passing frequency is now an important parameter as a modulation frequency (not as an infra-sound frequency). Human perception is most sensitive to modulation frequencies close to 4 Hz of sound with a frequency of approx. 1 kHz. The hypothesis that fluctuations are important is supported by descriptions given by naïve listeners as well as residents: turbines sound like ‘lapping’, ‘swishing’, ‘clapping’, ‘beating’ or ‘like the surf’. It is not clear to what degree this fluctuating character determines the relatively high annoyance caused by wind turbine sound and to a deterioration of sleep quality. Further research is necessary into the perception and annoyance of wind turbine sound, with correct assumptions on the level and character of the sound. Also the sound exposure level of fluctuations in the sound in the bedroom must be investigated to be able to assess the effects on sleep quality.

It is obvious that in wind turbine sound measurements atmospheric stability must be taken into account. When the impulsive character of the sound is assessed, this should be carried out in relation to a stable atmosphere, as that is the relevant condition for impulsiveness. Also sound immission should be assessed for stable conditions in all cases where night time is the critical noise period. Wind speed at low heights is not a sufficient indicator for wind turbine performance. Specifically, when ambient sound level is considered as a masker for wind turbine sound, neither sounds should be related to wind speed at reference height via a (possibly implicit) neutral wind profile. In stable conditions wind induced sound on a microphone is not as loud as is usually thought (creating a high background level lowering the ‘signal to noise ratio’), as in these conditions hub height wind speeds are accompanied by relatively low microphone height wind speeds. So, wind turbine sound measurements are easier when performed in a stable atmosphere, which agrees well with the night being the sensitive period for noise immission.

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## The Effect of Atmospheric Stability on Low Frequency Modulated Sound

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## LIST OF SYMBOLS

### Symbol: definition [unit]

$\alpha$ :	angle of attack [radian or degree]
$\delta_i^*$ :	displacement thickness of turbulent boundary layer [m]
$\nu$ :	kinematic viscosity of air [ $\text{m}^2 \text{s}^{-1}$ ]
$\rho$ :	correlation coefficient (here: between (1/3) octave band level and $L_A$ )
$\Omega$ :	turbine rotor angular velocity [ $\text{rad s}^{-1}$ ]
$a$ :	correction factor for boundary layer thickness (value: 2 – 4)
$c$ :	velocity of sound in air [ $\text{m s}^{-1}$ ]
$C$ :	blade chord length [m]
$D_h$ :	directivity function [-]
$f$ :	frequency [Hz]
$f_{\text{mod}}$ :	modulation frequency [Hz]
$f_{\text{peak,TE}}$ :	peak frequency of trailing edge sound [Hz]
$f_{\text{peak,if}}$ :	peak frequency of in-flow turbulence sound [Hz]
$f_B$ :	blade passing frequency [Hz]
$f_i$ :	$\alpha$ -dependent factor for boundary layer thickness [-]
$F_{\text{bb}}$ :	fluctuation strength [vacil]
$h$ :	height [m]
$H$ :	turbine height [m]
$h_{\text{ref}}$ :	reference height for wind speed (and direction) [m]
$k$ :	integer number (of harmonic frequency)
$K_1$ :	constant (128.5 dB)
$K_\alpha$ :	$\alpha$ dependent increase in trailing edge sound level [dB]
$M$ :	Mach number (at radius $R$ : $M = \Omega R/c$ ) [-]
$\Delta L$ :	increase in sound level [dB]
$L_A$ :	broad band sound level [dB(A)]
$L_{A5}$ :	5-percentile of broad band sound levels over a time period [dB(A)]
$L_{A95}$ :	95-percentile of broad band sound levels over a time period [dB(A)]
$m$ :	stability exponent [-]
$mf$ :	modulation factor [-]
$N$ :	number of blades [-]

$r$ :	distance [m]
$R$ :	rotor radius = blade length [m]
$\Delta R$ :	increment in $R$ [m]
$R_X$ :	range between maximum and minimum sound levels ( $X = \text{bb}$ or $f$ ) [dB]
$R_{X,90}$ :	range between 5- and 95-percentile of sound levels ( $X = \text{bb}$ or $f$ ) [dB]
$Re$ :	chord based Reynolds number ( $Re = \Omega RC/\nu$ ) [-]
$v_h$ :	wind speed at height $h$ [ $\text{m s}^{-1}$ ]
$v_{\text{ref}}$ :	wind speed at reference height [ $\text{m s}^{-1}$ ]
$v_{xx}$ :	wind speed at height $xx$ m [ $\text{m s}^{-1}$ ]
$Sp_i$ :	1/3 octave band weighing function for TE sound [dB]
$SPL_i$ :	sound pressure level [dB]
$St$ :	Strouhal number [-]

#### Subscripts:

$A$ :	A-weighted
$\text{bb}$ :	broad band
$f$ :	at frequency of (1/3) octave band
$i$ :	component of TE sound ( $i = p, s, \alpha$ )
$\text{if}$ :	in-flow
$p$ :	pressure side
$s$ :	suction side
$\text{TE}$ :	trailing edge

## APPENDIX I

### Dominant Sources of Wind Turbine Sound

With modern wind turbines there are three important mechanisms that produce sound. These will be reviewed here up to a detail that is relevant to this paper.

#### A. Infrasonid: thickness sound.

When a blade moves through the air, the air on the forward edge is pushed sideways, moving back again at the rear edge. For a periodically moving blade the air is periodically forced, leading to 'thickness sound'. Usually this will not lead to a significant sound production as the movement is smooth and thus accelerations are relatively small.

When a blade passes the turbine tower, it encounters wind influenced by the tower: the wind is slowed down, forced to move sideways around the tower, and causes a wake behind the tower. For a downwind rotor (*i.e.* the wind passes the tower first, then the rotor) this wake causes a significant change in blade loading.

The change in wind velocity near the tower means that the angle of attack of the air on a blade changes and lift and drag on the blade change more or less abruptly. This change in mechanical load increases the sound power level at the rate of the blade passing frequency,  $f_B$ . For modern turbines  $f_B = N \Omega / (2\pi)$  typically has a value of approximately 1 Hz. As the movement is not purely sinusoidal, there are harmonics with frequencies  $k f_B$ , where  $k$  is an integer. Harmonics may occur up to 30 Hz, so thickness sound coincides with the infrasound region (0–30 Hz). Measured levels at 92 m from the two-bladed 2 MW WTS-4 turbine showed that measured sound pressure levels of the individual blade harmonics were less than 75 dB, and well predicted by calculations of wind-blade interaction near the turbine tower [5, 6]. The envelope of the harmonics peaks at the fifth harmonic ( $k = 5$  with  $f_B = 1$  Hz), indicating a typical pulse time of  $(5 \text{ Hz})^{-1} = 0.2 \text{ s}$  which is 20% of the time between consecutive blade passages. The WTS-4 is a downwind turbine with an 80 m tubular tower, where the wind velocity deficit was estimated to be 40% of the free wind velocity [5]. For modern, upwind rotors the velocity deficit in front of the tower is smaller. As a consequence blade–tower wake interaction is weaker than for downwind turbines. From data collected by Jakobsen it appears that the infrasound level at 100 m from an upwind turbine is typically 70 dB(G) or lower, near downwind turbines 10 to 30 dB higher, where 95 dB(G) corresponds to the average infrasound hearing threshold [28]. Infrasound from (upwind) wind turbines thus does not appear to be so loud that it is directly perceptible.

## B. Low frequencies: in-flow turbulent sound.

Because of atmospheric turbulence there is a random movement of air superimposed on the average wind speed. The contribution of atmospheric turbulence to wind turbine sound is named ‘in-flow turbulence sound’ and is broad band sound stretching over a wide frequency range. For turbulent eddies larger in size than the blade this may be interpreted as a change in the direction and/or velocity of the incoming flow, equivalent to a deviation of the optimal angle of attack. This leads to the same phenomena as in A, but changes will be random (not periodic) and less abrupt. For turbulent eddies the size of the chord length and less, effects are local and do not occur coherently over the blade. When the blade cuts through the eddies, the movement normal to the wind surface is reduced or stopped, given rise to high accelerations and thus sound.

In-flow turbulence sound has a maximum level in the 1/3 octave band with frequency:

$$f_{\text{peak,if}} = (\text{St } 0.7R \Omega) / (H - 0.7R) \quad (\text{A1})$$

where Strouhal number St is 16.6 [4, 6]. Most sound is produced at the high velocity, outer parts of the blades. For a modern, tall, three-bladed wind turbine with hub height  $H = 100$  m, blade length  $R = 35$  m and angular velocity  $\Omega = 2\pi f_B / 3 = 2 \text{ rad s}^{-1}$  (20 rpm),  $f_{\text{peak,if}} = 11$  Hz which is in the infrasound region. Measured fall-off from  $f_{\text{peak,if}}$  is initially approx. 3 dB per octave, increasing to 12 dB per octave at frequencies in the audible region up to a few hundreds of hertz [4, 6].

## C. High frequencies: trailing edge sound.

Several flow phenomena at the blade itself or in the turbulent wake behind a blade cause high frequency sound (‘airfoil self-noise’). Most important for modern turbines is the sound from the turbulent boundary layer at the rear of the blade surface where the boundary layer is thickest and turbulence strength highest. Trailing edge sound has a maximum level in the 1/3 octave band with frequency

$$f_{\text{peak,TE}} = 0.02 \Omega R / (\delta^* M^{0.6}) \quad (\text{A2})$$

where Mach number M is based on airfoil velocity. The displacement thickness of the turbulent layer is:

$$\delta^* = a 0.37 C \text{Re}^{-0.2} / 8 \quad (\text{A3})$$

for a zero angle of attack. Re is the chord based Reynolds number [29]. The experimental factor a accounts for the empirical observation that the boundary layer is a factor 2 to 4 thicker than predicted by theory [3, 6]. For air of 10 °C and atmospheric pressure, a typical chord length  $C = 1$  m, and other properties as given above (section B),  $f_{\text{peak,TE}} = 1700/a$  Hz. With  $a = 2$  to 4,  $f_{\text{peak,TE}}$  is 450 – 900 Hz. The spectrum (see  $\text{Sp}_i$  below) is symmetrical around  $f_{\text{peak,TE}}$  and decreases with 3 dB for the first octave, 11 dB for the next, the contribution from further octave bands is negligible [29].

According to Brooks *et al.* [29] trailing edge sound level can be decomposed in components  $\text{SPL}_p$  and  $\text{SPL}_s$  due to the pressure and suction side turbulent boundary layers with a zero angle of attack of the incoming flow, and a component  $\text{SPL}_a$  that accounts for a non-zero angle of attack  $\alpha$ . For an edge length  $\Delta R$  each of the three components of the immission sound level at distance r can be written as [29]:

$$\text{SPL}_i = 10 \log(\delta_i^* M^5 \Delta R D_h / r^2) + \text{Sp}_i + K_i - 3 + K_i \quad (\text{A4})$$

and total trailing edge immission sound level as:

$$\text{SPL}_{\text{TE}} = 10 \log\left(\sum_i 10^{\text{SPL}_i / 10}\right) \quad (\text{A5})$$

where the index i refers to the pressure side, suction side or angle of attack part ( $i = p, s, \alpha$ ). The directivity function  $D_h$  equals unity at the rear of the blade ( $\theta = 180^\circ$ ) and falls off with  $\sin^2(\theta/2)$ . Because of the strong dependence on

**Table AI. Increase of trailing edge sound level with angle of attack  $\alpha$** 

A	1	2	3	4	5
$SPL_{TE}(\alpha) - SPL_{TE}(\alpha=0)$ (dB)	0.4	1.4	2.9	4.6	6.4

M ( $\sim M^5$ ) trailing edge sound is dominated by sound produced at the high velocity parts: the blade tips.

$Sp_i$  gives the symmetrical spectral distribution of the trailing edge sound spectrum centered on  $f_{peak,TE}$  and is maximum (0 dB) at this centre frequency. The constant  $K_1 - 3 = 125.5$  dB applies when the chord based Reynolds number exceeds  $8 \times 10^5$  and the pressure-side turbulent boundary displacement thickness  $\delta_1^* > 1$  mm, as is the case for modern tall turbines.  $K_i$  is non-zero only if  $i = \alpha$ .

For small non-zero angles of attack ( $\alpha < 5^\circ$ ) the boundary layer thickness shrinks  $\delta^*$  with a factor  $f_p = 10^{-0.042\alpha}$  at the pressure-side and grows with a factor  $f_s = 10^{0.068\alpha}$  at the suction-side;  $\delta_\alpha^* = \delta_s^*$ , so  $f_\alpha = f_s$ .

$K_\alpha$  has a large negative value for  $\alpha = 0$ . For  $1^\circ < \alpha < 5^\circ$  and  $M = 0.2$  it can be approximated by  $K_\alpha = 3.6\alpha - 12.1$  ([29], formula 49 with  $K_\alpha = K_2 - K_1 + 3$ ).

With equation A4, equation A5 can be rewritten as:

$$SPL_{TE} = 10 \log(\delta^* M^5 \Delta R D_h / r^2) + K_1 - 3 + 10 \log\left(\sum_i 10^{(10 \log(f_i) + Sp_i + K_i)/10}\right) \quad (A6)$$

The last term in A6 is the  $\alpha$ -dependent part. For the peak frequency 1/3 octave band level ( $Sp_i = 0$ ) the last term in equation A6 is 3 dB for  $\alpha = 0$ , and 4.4 dB at  $\alpha = 2^\circ$ , then increasing with approx. 1.7 dB per degree to 9.4 dB at  $\alpha = 5^\circ$ . The level increase relative to the level at  $\alpha = 0$  is given in table AI

The swishing sound that one hears when a blade passes the tower is less than 3 dB (in daytime) [8]. It must correspond to a change in sound level of 1 dB to be heard at all. An increase of 1 dB corresponds to an increase in  $\alpha$  from zero to a value of  $1.7^\circ$  (0.03 radians), an increase of 2 dB corresponds to  $2.5^\circ$  (0.04 radians). So we estimate the change in  $\alpha$  at the tower passage as  $2.1 \pm 0.4^\circ$ . Part of this is due to the lower wind velocity at the lower blade tip relative to the rotor average ( $0.8^\circ$ , see section 3 of main text), the rest is due to the slowing down of the wind by the tower.

For small angles the change of wind speed with angle of attack  $\alpha$  at radius R is:

$$dV_{wind}/d\alpha = \Omega R \quad (A7)$$

So for a modern turbine ( $\Omega R \approx 70$  m/s at tip at 20 rpm) the wind speed deficit where the blade tip passes the tower and  $\alpha = 2.1^\circ$  (0.037 radians) is 2.6 m/s. In a (rotor averaged) 14 m/s wind this is 20%. This deficit is due to the influence of the tower as well as the (daytime) wind profile.